NOAA–NASA Coastal Zone Color Scanner Reanalysis Effort

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Satellite observations of global ocean chlorophyll span more than two decades. However, incompatibilities between processing algorithms prevent us from quantifying natural variability. We applied a comprehensive reanalysis to the Coastal Zone Color Scanner (CZCS) archive, called the National Oceanic and Atmospheric Administration and National Aeronautics and Space Administration (NOAA–NASA) CZCS reanalysis (NCR) effort. NCR consisted of (1) algorithm improvement (AI), where CZCS processing algorithms were improved with modernized atmospheric correction and bio-optical algorithms and (2) blending where *in situ* data were incorporated into the CZCS AI to minimize residual errors. Global spatial and seasonal patterns of NCR chlorophyll indicated remarkable correspondence with modern sensors, suggesting compatibility. The NCR permits quantitative analyses of interannual and interdecadal trends in global ocean chlorophyll.
OCIS codes: 010.4450, 010.1290, 280.0280.

1. Introduction

NASA and the international scientific communities have established a record of nearly continuous, high-quality global ocean color observations from space since 1996. The Ocean Color and Temperature Scanner (OCTS; November 1996–June 1997), the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; September 1997–present), and the Moderate-Resolution Imaging Spectroradiometer (MODIS; September 2000–present) have provided an unprecedented view of chlorophyll dynamics on global scales by use of modern, sophisticated data processing methods. A predecessor sensor, the Coastal Zone Color Scanner (CZCS; November 1978–June 1986), utilized processing methodologies and algorithms that are outdated by modern standards. Thus the CZCS archive is severely limited for scientific analyses of interannual and interdecadal variability. This is an issue of fundamental importance to the study of global change.

In response, the National Oceanic and Atmospheric Administration (NOAA) and NASA established an effort to reanalyze the CZCS record by utilizing advances in algorithms that are shared by modern remote sensing missions. In this paper we describe the methods and results of this effort, called the NOAA–NASA CZCS Reanalysis Effort (NCR). Our methods involve the application of (1) recent algorithms to CZCS data to enhance quality and provide consistency with the modern sensors OCTS, SeaWiFS, and MODIS and (2) blending techniques[1] combining satellite data and the extensive *in situ* archives maintained by the National Oceanographic Data Center (NODC) Ocean Climate Laboratory (OCL) to minimize bias and residual error.

Our objective is to provide a high-quality blended satellite *in situ* data set that will enable a consistent view of global surface ocean chlorophyll and the primary production patterns in two observational time segments (1978–1986 and 1996–present) spanning two decades. By reconstructing the historical CZCS data set, we can gain new insights into the processes and interactions involved in producing the interannual and interdecadal chlorophyll signals.

2. Background

A. Coastal Zone Color Scanner and the Modern Ocean Color Sensors

The CZCS was a demonstration mission with two objectives: (1) to establish the technological and scientific feasibility of mapping ocean phytoplankton pigment concentrations from satellites and (2) to determine the improvements that must be made for successful follow-on ocean color missions. The CZCS amply demonstrated the first objective. It also clearly indicated deficiencies in its design and operations that required correction to meet the scientific objectives of a successor mission. In approximate order of priority, these deficiencies, or required improvements, were

(1) the need for routine, continuous global synoptic observations;
(2) better methods to characterize aerosols;
(3) the need for a dedicated calibration and validation program over the lifetime of the mission;
(4) methods to account for multiple scattering by aerosols and the interaction between scattering by molecules and aerosols;
(5) better signal-to-noise ratios (SNRs);
(6) the need to produce estimates of chlorophyll, not pigment;
(7) new information about chromophoric dissolved organic matter;
(8) the need to account for whitecap and foam reflectance; and
(9) improved pixel navigation.

All the modern global missions meet the scientific requirements for ocean color observations. They are dedicated, routine observational platforms. They contain spectral bands in the near-infrared region of the spectrum to enable improved determination of aerosol characteristics. Dedicated, high-quality *in* *situ* calibration and validation activities were established before launch. Complex algorithms were developed to account for aerosol multiple scattering and interactions with molecules. SNRs were improved so that all the global missions have at least 500:1 for the visible wavelengths[2] instead of 200:1 for the CZCS.[3] All the missions produce chlorophyll distributions as the primary geophysical product. A new spectral band was included at short wavelengths (near 410 nm) to help determine the distribution and abundance of chromophoric dissolved organic matter. Whitecap and foam reflectance algorithms were developed and refined. Finally, precise navigation methods were developed prelaunch, including improved orbit determination, sensor attitude information, and geolocation algorithms.

B. Coastal Zone Color Scanner Algorithm Deficiencies

Of course, some of the deficiencies of the CZCS data set, such as sensor design and operation activities, cannot be improved after the fact. However, recent advances in our understanding of atmospheric and oceanic optical principles that affect ocean color observations can be applied to the archive. The global CZCS data archive generally available from the NASA Goddard Earth Sciences (GES) Distributed Active Archive Center (DAAC) was produced in 1989 with algorithms that were standard for the time.[4] All the subsequent algorithm improvements (AIs) are utilized in the atmospheric correction and bio-optical algorithms for the modern sensors OCTS, SeaWiFS, and MODIS and in future sensors such as the medium resolution imaging spectrometer, Global Imager, and the visible infrared imaging radiometer suite.

The CZCS archive contains eight major algorithm deficiencies compared with modern sensors: (1) calibration, (2) navigation, (3) constant aerosol type, (4) single-scattering approximation for aerosols and no Rayleigh–aerosol interaction, (5) production of pigment rather than chlorophyll, (6) lack of whitecap and foam reflectance correction, (7) lack of correction to Rayleigh scattering because of nonstandard atmospheric pressure, (8) lack of accounting for water-leaving radiance at 670 nm in high chlorophyll.

These deficiencies affect the representation of global chlorophyll and are a major reason for differences observed between the CZCS era and the modern satellite observations of chlorophyll (shown in Section 4).

C. Blending of Coastal Zone Color Scanner and *in situ* Data for Analysis of Seasonal Variability

Gregg and Conkright[1] combined the extensive archive of NOAA NODC OCL chlorophyll data (>130,000 profiles) with the global CZCS archive at the GES DAAC using the blended analysis of Reynolds[5] to improve the quality and accuracy of global chlorophyll seasonal climatologies. The blended analysis produced a dramatically different representation of global, regional, and seasonal chlorophyll distributions than the archived CZCS.[1] Generally, the CZCS appeared to underestimate chlorophyll concentrations globally by 8–35%. On regional and seasonal scales, larger underestimates were common (20–40%, and occasionally the differences exceeded 100%).

Although the blending approach appeared to have improved many of the deficiencies of the CZCS seasonal climatologies, vast areas of the ocean lacked *in situ* observations, limiting the ability of the method to correct for the deficiencies in the CZCS processing. Further improvements by use of the blended method require better CZCS data.

5. Summary and Conclusions

We revised the CZCS global ocean chlorophyll archive using compatible atmospheric correction and bio-optical algorithms with modern generation ocean color sensors, such as OCTS, SeaWiFS, and MODIS. The revision involved two components: (1) AI, where CZCS processing algorithms were improved to take advantage of recent advances in atmospheric correction and bio-optical algorithms; and (2) blending, where *in situ* data were incorporated into the final product to provide improvement of residual errors. The combination of the two components is referred to as the NOAA–NASA CZCS reanalysis effort. The results of the NCR are compared with *in situ* data and indicate major improvement from the previously available CZCS archive maintained by the NASA GES DAAC. Blending with *in situ* data produced only a 21% adjustment to the CZCS AI field, compared with a 75% percent adjustment required for the DAAC CZCS. This represented a 72% improvement. Global annual means for the NCR suggested a small overestimate of 9.7% from the CZCS AI, compared with a mean 26% underestimate for the DAAC CZCS blend. Frequency distributions of normalized water-leaving radiances at 520 and 550 nm were in close agreement with expected. Finally, observations of global spatial and seasonal patterns indicated remarkable correspondence with SeaWiFS, suggesting data set compatibility.

This revision can permit a quantitative comparison of the trends in global ocean chlorophyll from 1979–1986, when the CZCS sensor was active, to the present, beginning in 1996 with OCTS, SeaWiFS, and MODIS. The overall spatial and seasonal similarity of the data records of CZCS and SeaWiFS strongly suggests that differences are due to natural variability, although some residual effects that are due to CZCS sensor design or sampling may still exist. We believe that this reanalysis of the CZCS archives can enable identification of interannual and interdecadal change. NCR CZCS data are available through the GES DAAC.